Observation of an abrupt disruption of the long-term warming trend at the Balearic Sea, western Mediterranean Sea, in summer 2005

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[1] The properties of the Western Mediterranean Deep Water in a wide area located at the western boundary of the Mediterranean Sea, including the Balearic Sea, have revealed intense changes when observed in summer 2005. Between February and June 2005, a temperature drop of 0.14°C reverted dramatically the progressive warming trend of 0.011°C yr^{-1} that had been observed since 1996, in the waters below 600 dbar north of the Balearic channels. A similar temperature drop has been observed east of the Minorca Island, below the Levantine Intermediate Water and down to 1500 dbar. In the deepest levels, a complex thermohaline structure, which implies different waters masses as sources, was tracked more than 400 km along the western boundary of the Mediterranean Sea, from Barcelona to the Algerian Basin. It is suggested that the changes may be linked to the severe 2004/2005 winter occurred at the northwestern Mediterranean Sea.
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1. Introduction

[2] It is well known that the Western Mediterranean (WM) basin is immersed in a process of warming and salt-increase since, at least, the beginning of the 20th century. According to the work of *Bethoux et al.* [1998] the Western Mediterranean Deep Water (WMDW) has increased, between 1959 and 1997, 0.13°C (0.0035°C yr^{-1}) its temperature and 0.04 (0.001 yr^{-1}) its salinity. In addition, a 0.09°C warming and a 0.035 salt-increase have been reported for the water column below 600 dbar in the period 1950–2000 [*Rixen et al.*, 2005]. The observed long-term warming of the WMDW is comparable with the warming of the upper layer of the world oceans (0.006°C yr^{-1}; 1948–1998; [*Levitus et al.*, 2000]), and with the warming of the mid-depth levels of the North Atlantic (0.005°C yr^{-1}; 1920s - 1990s [*Arbic and Owens*, 2001]). After the middle of the 20th century, the warming trend of the WM has accelerated [*Rohling and Bryden*, 1992], specially during the last 15 years [*Rixen et al.*, 2005], with local trends at shorter periods as high as 0.016°C yr^{-1} for the deep water in the Tyrrhenian Sea [*Fuda et al.*, 2002]. The faster warming is consistent with the changes observed in the nearby Atlantic main thermocline waters during the same decade, with trends over 0.020°C yr^{-1} and reaching 0.040°C yr^{-1} [*Vargas-Yanez et al.*, 2004; *Gonzalez-Pola et al.*, 2005]. This increase in the warming trend of the WM is consistent with the fact that the climatic warming has accelerated during the last two decades of the 20th century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001].

[3] The high correlation between the WMDW and the North Atlantic water properties and the NAO index [*Rixen et al.*, 2005], and the fact that warming and salt-increase of these waters have been attributed to several causes as changes in atmospheric conditions including decreasing precipitation, greenhouse warming and/or to the anthropogenic reduction of the freshwater flux [*Rohling and Bryden*, 1992; *Krahmann and Schott*, 1998; *Bethoux et al.*, 1998] makes this water mass an important indicator of basin-scale or global changes.

[4] In this work, a 10-year time-series of θS properties at two hydrograpic stations in the Balearic Sea and a set of deep profiles sampled during July 2005 in the western boundary of the Mediterranean Sea (Figure 1) are analyzed. It is shown that the properties of the WMDW in the western boundary of the WM have been strongly modified. North of the Balearic channels, a temperature drop that compensates the temperature increase accumulated during the last ten years has been observed. The possible causes of the observed changes are discussed, considering the severe weather conditions of the 2004/2005 winter occurred at the so-called MEDOC site, the area in the Gulf of Lion where the WMDW is formed by deep convection [*MEDOC Group*, 1970].

2. Data Set

[5] As part of the Instituto Español de Oceanografía (Spanish Institute of Oceanography) research core program, the CANALES and CIRBAL projects have been carried out consecutively since 1996 to study the north/south flux interchange at the Ibiza and Majorca channels (Figure 1). Several transects are visited at different seasons every year, and two deep hydrographic stations, 33 (1360 m) and 25 (1250 m, data not shown), have been sampled 25 and 24 times respectively since 1996, providing with a complete picture of the interannual and seasonal variability of the water masses at the area. As an observation opportunity under the TUNIBAL project, designed to study the influence of the environmental factors on the spawning strategy of the bluefin tuna in the Balearic Sea, the deep hydrographic station C east of Minorca was visited in the 2001, 2003, 2004 and 2005 summers. During the TUNIBAL July 2005 cruise, deep

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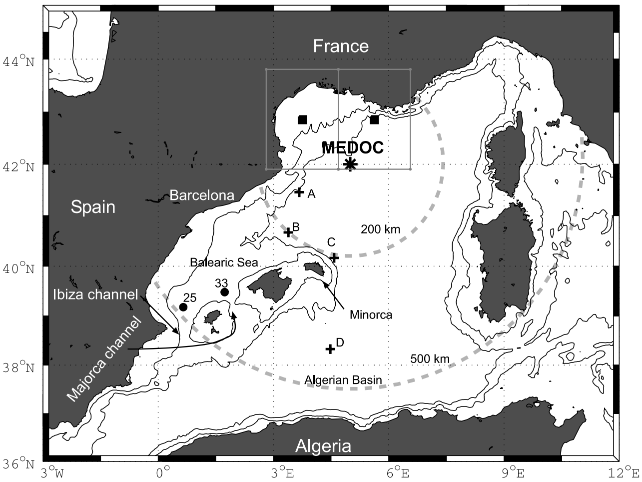

Figure 1. Western Mediterranean Basin. Stations 33 (north of Majorca channel, 1360 m) and 25 (north of Ibiza channel, 1250 m, data not shown) have been regularly occupied since 1996. Stations A, B, C and D (crosses) along the western boundary of the WM were visited in July 2005. Station C was also occupied in the 2001, 2003 and 2004 summers. The asterisk represents the center of the MEDOC area and the dashed lines are range-rings of 200 and 500 km from the MEDOC area. The isobaths correspond to 600 m and 2000 m. The filled squares represent the center of the grid points of the NCEP reanalysis used to compute the mean heat fluxes (thin gray rectangles, 133 × 212 km) and correspond to the northwestern-most sea-cells in the model.

CTD casts at stations A, B and D were made in order to address the spatial distribution of the observed changes. All CTD casts were carried out with SBE25 and SBE911 probes calibrated to comply with the required data quality. The changes observed during summer 2005 were also contrasted with deep profiles from ARGO floats (data not shown). The air-sea fluxes at the MEDOC area, available since 1948, were taken from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996].

3. Results

[6] The weather conditions during the 2004/2005 winter were particularly severe in Southwestern Europe without precedent during the last 40 years, with five intense polar fronts reaching the Mediterranean coast of Spain and the Balearic Islands. Following the NCEP reanalysis, the mean winter heat flux loss at the MEDOC area, averaged between December 2004 and March 2005, was ≈210 Watt m^{-2}, the highest since 1948, 75% higher than the ≈120 Watt m^{-2} winter average value since 1948 and 70% higher than the winter average value between 1996–2005, the period covered by the hydrographic time-series (Figure 2a).

[7] During the same 1996–2005 period, the θS properties at station 33 suffered a progressive warming and salt-increase trend in the waters deeper than 600 dbar (to compare with the work of *Rixen et al.* [2005]) of 0.011 ± 0.004°C yr^{-1} for potential temperature, 0.003 ± 0.001 yr^{-1} for salinity, but without density (σ_θ) trend 0.000 ± 0.001 kg m^{-3} yr^{-1} (Figure 2). The trends at station 25 were similar, but the confidence intervals are higher since the Ibiza channel presents a more energetic dynamics. Although it is uncertain the spatial extent where these local trends may be extrapolated, until march 2005 they were similar to those reported for the whole Western Mediterranean Sea, and somehow accelerated as in other regions of the basin [*Fuda et al.*, 2002]. However, the measurements in June 2005 revealed a dramatic drop in potential temperature at both stations of 0.14°C, higher than the accumulated increase observed since 1996, and higher than the reported net accumulated warming of the whole WMDW during the last half century. The salinity also decreased appreciably, but just in a magnitude slightly higher than the interannual variability, and consequently the density of the whole water column rose significantly.

[8] Although the Balearic Sea may be influenced, compared with other parts of the WM, by a direct pathway in the spreading of the newly formed WMDW as indicated in the work by *Millot* [1999] and as shown by the trajectories of RAFOS floats [*Send et al.*, 1999], station C Northeast of Minorca Island, which was visited in the 2001, 2003, 2004 and 2005 summers (Figures 3a and 3b), has confirmed that changes also reached the Algero-Provençal basin. Despite of the unresolved interannual variability of these profiles, the 0.12°C potential temperature drop and the 0.015 decrease in salinity found in this station between 2004 and 2005 in the 600–1400 dbar water column, suggest a similar behavior for a wide area. The observations at stations A, B, C and D in summer 2005 (Figures 3e and 3f) show a very striking structure, which has few similar cases in the Med-Atlas database [*MEDAR Group*, 2002]. Below 1400 dbar, the potential temperature profiles instead of being constant or

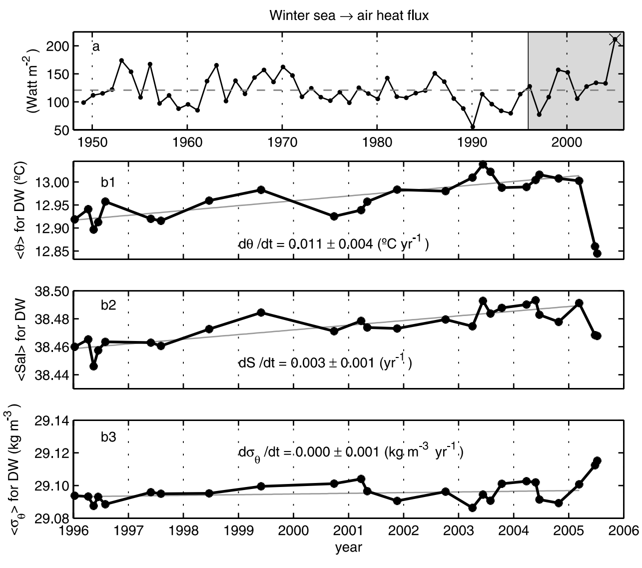

Figure 2. (a) Time series of heat flux loss (sea to air) from the NCEP/NCAR reanalysis dataset, averaged from December to March at the two grid points located at the MEDOC area (Figure 1). If the two cells located immediately below were taken into account the strong anomaly would be similar. The gray box indicates the period of time covered by the hydrographic time series north of the Balearic channels. (b) Time series, at station 33, of seawater properties averaged from 600 dbar down to the bottom. The trends have been computed with data until March 2005.

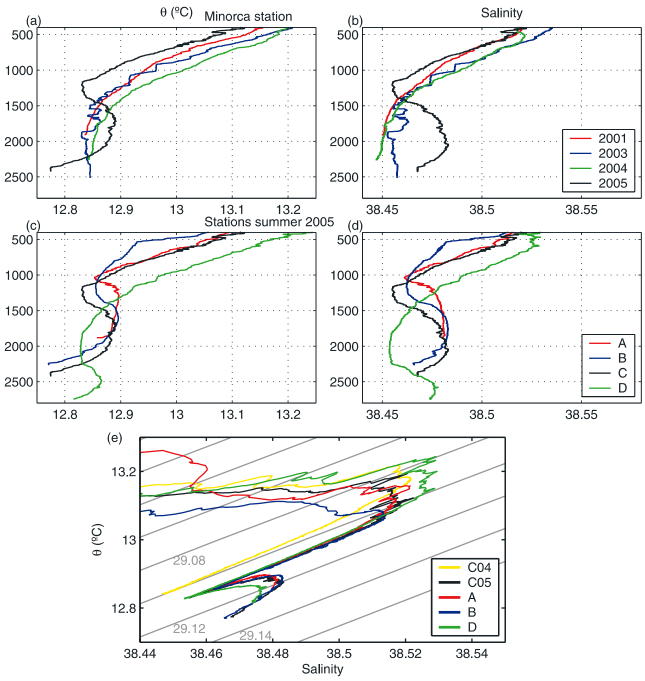

Figure 3. (a) Potential temperature and (b) salinity profiles at station C for different summers. (c) Potential temperature and (d) salinity profiles observed during July 2005 along stations in the western margin of the WM (indicated in Figure 1). (e) θS diagram from profiles carried out during summer 2005, and including station C in 2004 (very similar to those observed in 2001 and 2003) for comparison.

with a slight gradient down to the bottom, shows a strong inversion towards higher values than those found in previous years. Below 2000 dbar, the potential temperature presents a strong gradient back towards very low values. Salinity shows a pattern similar to that described for potential temperature.

[9] In the θS diagram (Figure 3e) the same peculiar thermohaline structure is observed for all the stations sampled during the summer 2005, station A, northeast of Barcelona at 125 km from the center of the MEDOC area, shows the transition depth, where θ begins to rise, at about 1000 dbar instead of 1400 dbar as found in station C. Station B, located halfway between the MEDOC area and the Balearic Sea and at the same distance from the MEDOC area than station C (200 km and 207 km), shows exactly the same structure, including the same transition depth and hence suggesting an isotropic spreading of the WMDW towards the Balearic Sea and the east of Minorca. Station D, located at the Algerian basin and 410 km away from the MEDOC area, present the transition depth located at 2200 dbar and the anomaly is felt down to the bottom (2700 dbar). All the deep waters showing the new structure, and above it, have raised significantly its density if compared with previous occupations of station C.

4. Discussion and Conclusions

[10] The changes found in the WMDW may be related either to the severe weather conditions occurred during the 2004/2005 winter at the area of formation of WMDW, as suggested by the air-sea fluxes, or/and to alterations in the water masses advected to the sampling area; the later due to changes in the properties of the advected water masses themselves or variations in the circulation patterns. Besides the local drop of the warming trend detected north of the Balearic channels and east of Minorca in the 600–1400 dbar layer, the complex structure that has emerged below the cooled level raises questions about the different sources contributing to the final WMDW.

[11] *Bethoux et al.* [2002] analyzed some thermal inversions in WMDW during specific years and tracked them along the WM basin. Based on turbidity measurements, volume budget considerations and current-meter series they concluded that these structures come from cascading of dense water along the Gulf of Lion canyons. The structure found during summer 2005 is more complex and it is not easily explained without considering more water masses as sources as well as the old WMDW. Besides the typical deep water production at the MEDOC area it is feasible that strong cascading may have taken place in winter 2005 and also it may be considered the possibility of different deep water formation events from December to March. If the structure were linked to the strong winter, the fact that it was found far from the MEDOC area 4–5 months after the winter events reinforces the previously estimated spreading velocities of 3.5 to 5 cm s^{-1} for the newly formed waters [*Send et al.*, 1996; *Bethoux et al.*, 2002]. Apart from that, other water masses contributing to WMDW (including Tyrrhenian Deep Water after the work of *Rhein et al.* [1999]) may have suffered alterations. The Eastern Mediterranean Transient (EMT) [*Lascaratos et al.*, 1999; *Robinson et al.*, 2001] has been recently associated to water mass modifications in the western basin and also to variations in the interchange between the eastern and western Mediterranean through the Sicily strait [*Astraldi et al.*, 2002]. These changes are a plausible candidate to influence deep water production in the Western Mediterranean as it was suggested by *Roether et al.* [1996]. It has been also proposed recently that WMDW may be currently being replaced by waters coming from the eastern Mediterranean and therefore extending the EMT to a Mediterranean Sea Transient [*Millot*, 2005].

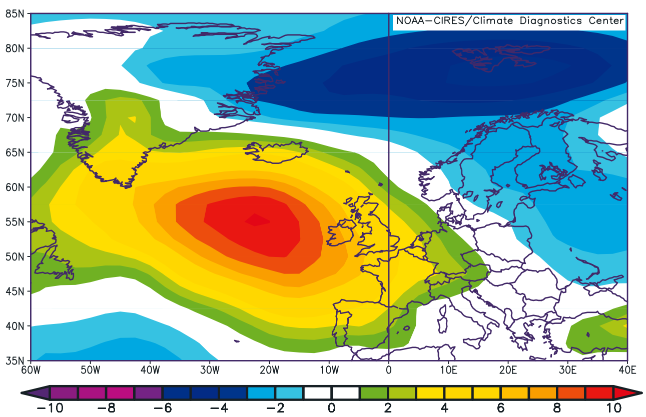

Figure 4. Mean 2005 winter (December 2004 to March 2005) sea level pressure anomaly (mb) with respect the 1968–1996 climatological field. NCEP/NCAR Reanalysis data from NOAA-CIRES Climate Diagnostics Center.

[12] It is interesting to point out that the WM have only one important area of deep water formation (by means of deep convection) that represents a relatively small area in the context of global atmospheric patterns. This WMDW source may be extremely active one year due to a specific local atmospheric configuration. Particularly, the 2004/2005 winter at the southwestern Europe (including the MEDOC area) was dominated by an anomalous atmospheric pattern: a strong anticyclone located west of the British Islands that lasted for the whole winter (Figure 4) produced intense and persistent cold and dry northerly winds over the MEDOC area, as well as the recurrent arrival of polar fronts which resulted in a large heat flux anomaly at the Gulf of Lion (Figure 2a). The fact that the center of this pressure anomaly was located halfway between Iceland and the Azores archipelago determined that the NAO-index for the 2005 winter resulted zero on average. Specifically, the principal component based NAO_{DJFM} (December to March) index [*Hurrell*, 1995] is 0.48 (slightly positive), while the Gibraltar and Reykjavik station based winter NAO-index is -0.11 (slightly negative). Consequently, the strong sea to air flux in the Gulf of Lion during winter 2005, the highest ever measured, is not linked to a strong negative NAO index as it should follows from the correlation found by *Rixen et al.* [2005] between these magnitudes, thus making the 2005 winter an unusual one.

[13] Despite that neither the causes of the observed changes nor precise quantifications can be precisely determined from the current data set, it is clear that at least part of the deep Western Mediterranean presents currently a new structure. The changes seem to have occurred quite abruptly and whether or not they are an isolated event or the first stage of a long-lasting change should be studied and monitored in the future.

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